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(54) **ROTATING CATHETER PROBE USING A LIGHT-DRIVE APPARATUS**

(71) Applicant: **Board of Regents, The University of Texas System**, Austin, TX (US)

(72) Inventors: **Thomas E. Milner**, Austin, TX (US); **Nathaniel J. Kemp**, Concord, MA (US)

(73) Assignee: **Board of Regents, The University of Texas System**, Austin, TX (US)

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A61B 1/00 (2006.01)

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See application file for complete search history.

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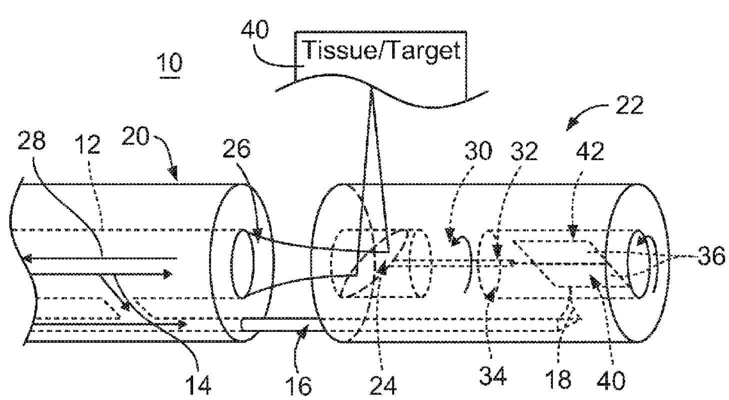
Primary Examiner — Rajeev Siripurapu
(74) *Attorney, Agent, or Firm* — J. Peter Paredes; David G. Rosenbaum; Rosenbaum IP, P.C.

(57) **ABSTRACT**

The invention is a rotating tip catheter-imaging probe where electromagnetic energy is delivered to the distal end of a catheter and converted to mechanical energy using a light drive apparatus. The mechanical energy is then used to rotate a mirror that redirects light in fixed pattern on a sample. The rotating element of the light drive apparatus contains vanes, which rotate about an axis and positioned with bearings to minimize friction. A chamber encompasses the rotating element and is set to a vacuum pressure. The rotational speed of the catheter tip can be controlled by varying the optical power delivered to the vanes, the vacuum pressure in the chamber, or by a braking mechanism applied to the rotating element. The vanes may be shaped in a particular geometry to increase forces on the vanes from thermally driven gas flow.

11 Claims, 2 Drawing Sheets



Related U.S. Application Data

continuation of application No. 11/567,244, filed on Dec. 6, 2006, now Pat. No. 7,844,321, which is a continuation-in-part of application No. 10/548,982, filed as application No. PCT/US2004/012773 on Apr. 23, 2004, now Pat. No. 7,711,413.

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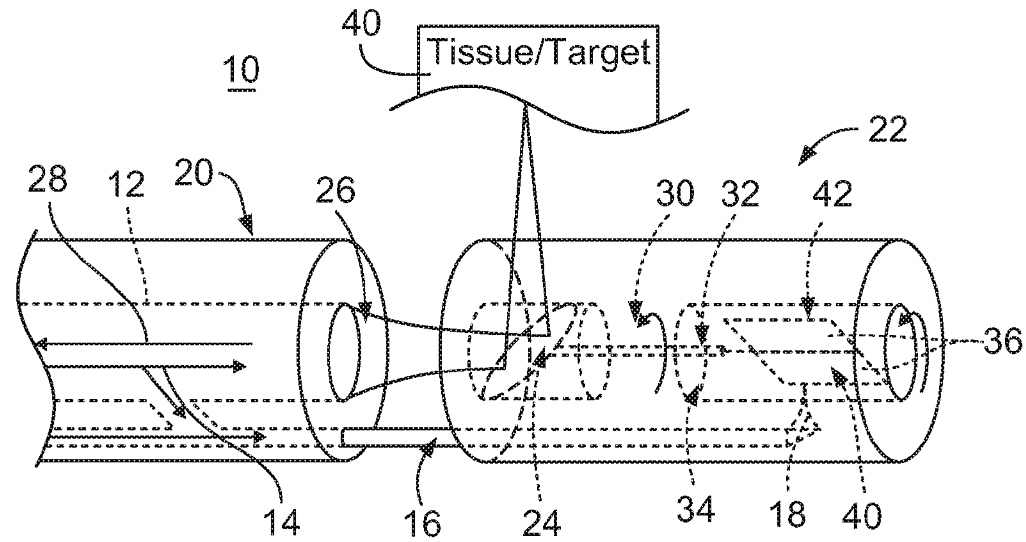

FIG. 1

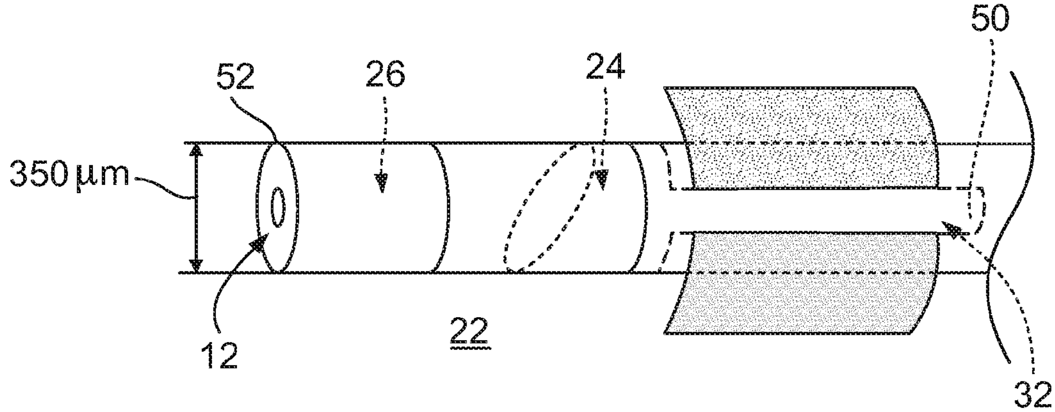

FIG. 2

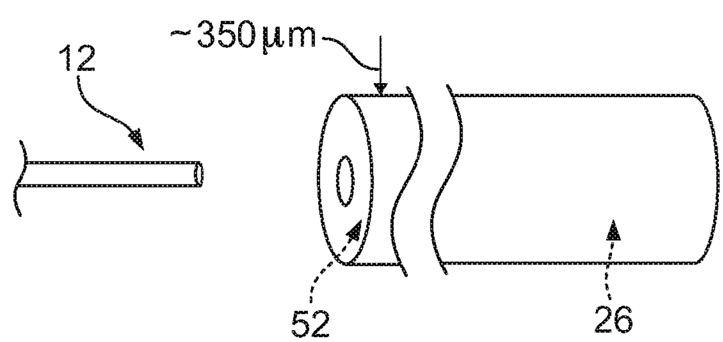

FIG. 3

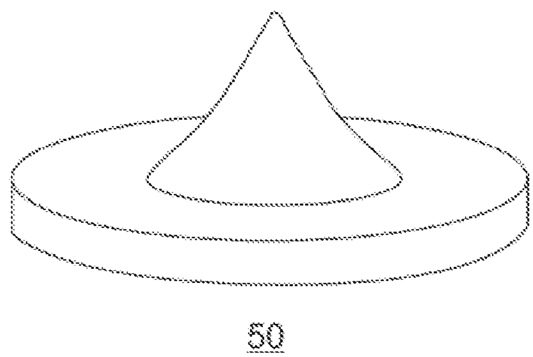

FIG. 4

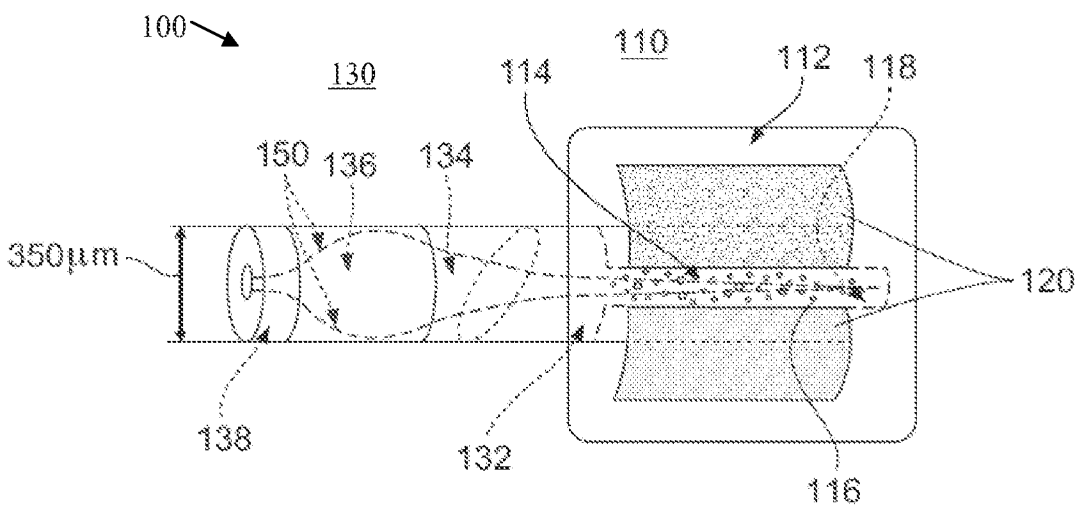

FIG. 5

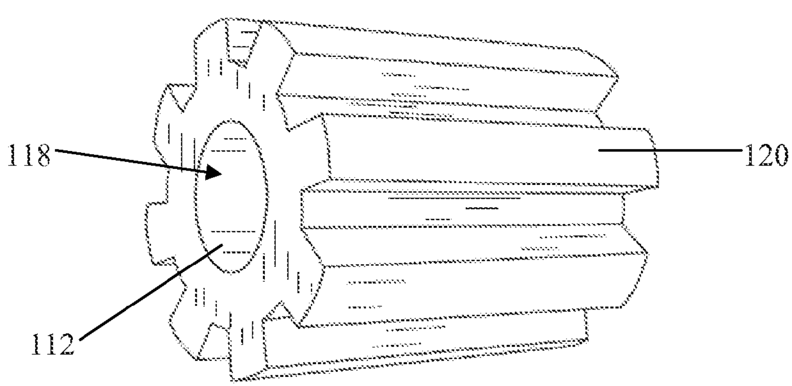

FIG. 6

ROTATING CATHETER PROBE USING A LIGHT-DRIVE APPARATUS

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is divisinal of U.S. patent application Ser. No. 12/902,092, filed Oct. 12, 2010, which is a continuation of U.S. patent application Ser. No. 11/567,244, filed Dec. 6, 2006, now U.S. Pat. No. 7,844,321, which is a continuation-in-part of U.S. patent application Ser. No. 10/548,982, which was filed Sep. 7, 2005 and granted a U.S. national stage filing date of May 2, 2006, now U.S. Pat. No. 7,771,413, which claims priority to PCT International Patent Application No. PCT/US2004/012773, filed Apr. 23, 2004 and which claims priority to U.S. Provisional Patent Application Ser. No. 60/466,215, filed Apr. 28, 2003, all of which are hereby expressly incorporated by reference in their entireties.

STATEMENT OF GOVERNMENT SUPPORT

This invention was made with government support under Grant No. R01 EY016462 awarded by the National Institutes of Health. The government has certain rights in the invention.

BACKGROUND

The present invention relates generally to catheter probes, which direct optical energy for diagnostic or therapeutic purposes. More specifically, the invention relates to catheter probes using optical coherence tomography having a fixed or stationary optical imaging fiber.

Generally speaking, Optical Coherence Tomography ("OCT") is a technology that allows for non-invasive, cross-sectional optical imaging of biological media with high spatial resolution and high sensitivity OCT is an extension of low-coherence or white-light interferometry, in which a low temporal coherence light source is utilized to obtain precise localization of reflections internal to a probed structure along an optic axis. This technique is extended to enable scanning of the probe beam in the direction perpendicular to the optic axis, building up a two-dimensional reflectivity data set, used to create a cross-sectional gray-scale or false-color image of internal tissue backscatter.

OCT uses a superluminescent diode source or a tunable laser source emitting a 1300 nm wavelength, with a 50-250 nm bandwidth (distribution of wave length) to make in situ tomographic images with axial resolution of 2-20 μm and tissue penetration of 2-3 mm. OCT has the potential to image tissues at the level of a single cell. In fact, the inventors have recently utilized broader bandwidth optical sources, so that axial resolution is improved to 4 μm or less. With such resolution, OCT can be applied to visualize intimal caps, their thickness, details of their structure including fissures, the size and extent of the underlying lipid pool, and the presence of inflammatory cells. Moreover, near infrared light sources used in OCT instrumentation can penetrate into heavily calcified tissue regions characteristic of advanced coronary artery disease. With cellular resolution, application of OCT may be used to identify other details of the vulnerable plaque such as infiltration of monocytes and macrophages. In short, application of OCT can provide detailed images of a pathologic specimen without cutting or disturbing the tissue.

OCT can identify the pathological features that have been associated with vulnerable plaques. The distal end of the optical fiber is interfaced with a catheter for interrogation of the coronary artery during a heart catheterization procedure. The reflected light from the plaque is recombined with the signal from the reference mirror forming interference fringes (measured by a photovoltaic detector) allowing precise depth-resolved imaging of the plaque on a micron scale.

An OCT catheter to image coronary plaques have been constructed. (Jang I K, Bouma B E, Hang O H, et al. Visualization of coronary atherosclerotic plaques in patients using optical coherence tomography: comparison with intravascular ultrasound. JACC 2002; 39: 604-609, incorporated by reference herein). The prototype catheter consists of a single light source and is able to image over a 360-degree arc of a coronary arterial lumen by rotating a shaft that spins the optical fiber. Because the rotating shaft is housed outside of the body, the spinning rod in the catheter must rotate with uniform angular velocity so that the light can be focused for equal intervals of time on each angular segment of the coronary artery. Mechanical drag in the rotating shaft can produce significant distortion and artifacts in recorded OCT images of the coronary artery. Unfortunately, because the catheter will always be forced to make several bends between the entry point in the femoral artery to the coronary artery (e.g., the 180 degree turn around the aortic arch), uneven mechanical drag will result in OCT image artifacts As the application of OCT is shifted from imaging gross anatomical structures of the coronary artery to its capability to image at the level of a single cell, non-uniform rotation of the single fiber OCT prototype will become an increasingly problematic source of distortion and image artifact.

Consequently, endoscope type single channel OCT systems suffer from non-constant rotating speed that forms irregular images of a vessel target. See U.S. Pat. No. 6,134,003, which is hereby incorporated by reference. The use of rotating single mode fibers is prone to artifact production in the OCT image. The catheter will always be forced to make several bends from its entry in the femoral artery, to the 180-degree turn around the aortic arch, to its final destination in the coronary artery. All these bends will cause uneven friction on the rotary shaft, and uneven time distribution of the light on the entire 360-degree arch of the coronary artery. As the application of OCT is shifted from gross anatomical structures of the coronary artery to its capability to image at the level of a single cell, then non-uniform rotation of the single fiber OCT will become even a greater source of image artifact.

The present invention overcomes many of the problems associated with transducing motion in remote locations such as the distal end of an optical or ultrasonic imaging catheter inside the body, such as non-uniform rotational distortion (NURD) associated with direct mechanical actuation along a shaft, biocompatibility hazards associated with delivering substantial electrical currents or voltages to actuate motors or magnets, biocompatibility hazards and fluid dynamic limitations associated with using pressurized liquid or gas to actuate a turbine. The advantage of the present invention is that it delivers light to the internal volume of the thermal gradient, which is more efficient and less constrained.

SUMMARY OF THE INVENTION

The present invention is a rotating catheter probe where optical energy is delivered to the distal end of a catheter and converted to mechanical energy using a light drive apparatus. The light drive apparatus functions as a drive turbine to

rotate a prism that redirects light onto a sample. The rotating element includes at least one vane member on a rotary axle, which is mounted on a posterior bearing and an anterior bearing to minimize friction. The rotating element is mounted in a vacuum chamber or capsule, which is, in turn, mounted at a distal end of a catheter and coaxial with an optical fiber, which passes down the length of the catheter. The rotational speed of the rotating element is proportional to the optical power applied to the vanes, and may be controlled by varying the optical power, varying the vacuum pressure in the chamber or capsule, or by a braking mechanism applied to the rotary axle. The vanes may be shaped in a particular geometry to maximize the thermal transpiration forces on the vanes.

Another embodiment of the invention is a method for delivering optical energy to a target for therapeutic or diagnostic purposes.

Another embodiment of the invention is a method of making a rotating tip catheter-imaging probe.

The methods, systems, and apparatuses are set forth in part in the description which follows, and in part will be obvious from the description, or can be learned by practice of the methods, apparatuses, and systems. The advantages of the methods, apparatuses, and systems will be realized and attained by means of the elements and combinations particularly pointed out in the appended claims. It is to be understood that both the foregoing general description and the following detailed description are exemplary and explanatory only and are not restrictive of the methods, apparatuses, and systems, as claimed.

BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying figures, like elements are identified by like reference numerals among the several preferred embodiments of the present invention.

FIG. **1** is a diagram representation of the light drive apparatus coupled to an optical fiber.

FIG. **2** is perspective view of the light drive apparatus for imparting rotational force to a prism in a catheter.

FIG. **3** is a perspective exploded view depicting a bearing and Gradient Index (GRIN) lens in accordance with a first embodiment of the present invention.

FIG. **4** is perspective view of an embodiment of the posterior bearing

FIG. **5** is a perspective view of an embodiment of the light drive apparatus for imparting rotational force to a prism in a catheter illustrating light propagation through the device.

FIG. **6** is a perspective view of an embodiment of a rotor drive in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The foregoing and other features and advantages of the invention are apparent from the following detailed description of exemplary embodiments, read in conjunction with the accompanying drawings. The detailed description and drawings are merely illustrative of the invention rather than limiting, the scope of the invention being defined by the appended claims and equivalents thereof.

The present invention relates to U.S. Provisional Patent Application Ser. No. 60/466,215 filed Apr. 28, 2003 (the '215 Provisional) and to PCT International Application No. PCT/US2004/012773 (the "773 PCT Application") filed Apr. 23, 2004, which designates the United States each of which is hereby incorporate by reference. The '215 Provisional and the '773 PCT Application disclose a catheter imaging probe for conducting optical coherence tomography in which light from a fixed or stationary optical fiber is directed onto a rotating prism or mirror. The prism or mirror is connected to a rotating rotor, which is driven by either fluid, such as liquids or gases, or by electromotive, or magnetomotive forces. As used in this application the term "catheter" is any device for bringing the probe within or without the body for scanning purposes, such as an endoscope, bronchoscope, laparoscope, otheoscope, catheter, or other similar devices.

Generally speaking, the present invention is a rotating catheter probe **10**, where optical energy **14** is delivered to the distal end of a catheter housing **20** and converted to mechanical energy **30** using a light drive apparatus **22**, as shown in FIG. **1**. The light drive apparatus **22** rotates a prism **24**, by thermal transpiration or thermal creep, resulting from the transduction of mechanical energy **30** from optical energy **14** applied to the light drive apparatus **22**. An optical fiber **12** delivers the optical energy **14**, which is also focused by a lensing element **26** onto the prism **24**. When the light drive apparatus **22** rotates the prism **24**, the prism **24** then redirects optical energy **14** away from the longitudinal axis of the catheter housing **20** and onto a target **40** while traversing a 360-degree arc. The optical fiber **12** does not rotate at all during the rotation of prism **24**, and is able to receive backreflected light from the target **40**. In one embodiment, the prism **24** is a mirrored prism, a totally-internally reflecting prism, or a dichroic reflector. The target **40** can be a blood vessel wall, or any target in which it is desired to direct optical energy. It should be appreciated that the light drive apparatus **22** can be used for other optical imaging systems or spectroscopic measurement devices, where optical energy is to be delivered and collected.

As shown in FIG. **1**, the prism **24** is operably connected to the light drive apparatus **22** by a rotary axle **32**, which extends distally from the prism **24**. The distal end of the rotary axle **32** is operably connected to the light drive apparatus **22** through a chamber **34**. Within the capillary tube **34**, the light drive apparatus **22** includes a plurality of vanes **36** extending radially outward from the rotary axle **32**. A first absorbent surface **42** of each vane **36** is coated with an energy absorbing material, such as black electrophoretic ink or powder black; while a second reflective surface **40** of each vane **36** is coated with an energy reflecting material, such as a metallization layer. A thermal isolating material can be used to isolate the absorbent surface **42** of the vane from the reflective surface **40**, either by imposing it between the two surfaces or by applying a thermal insulator to the entire assembly prior to the coatings. It is to be understood that the first absorbent surface **42** and second reflective surface **40** provide a thermal gradient between the two surfaces. Any such material, surface, or coating providing a thermal gradient is encompassed by surfaces **40** & **42**, as readily apparent to those skilled in the thermal arts.

The plurality of vanes **36**, the axle **32**, and a power transmitting fiber **16** comprises the light drive apparatus **22**. The power transmitting fiber **16** transmits optical energy **14** to the absorbent surface **42** of the vanes **36** to induce thermal transpiration and consequently rotate the axle **32** and the prism **24**. The power transmitting fiber **16** can include a reflecting element to transmit optical energy **14**. Alternatively, a multi-mode fiber or a single-mode fiber can be used as the power transmitting fiber **16**, which can be coupled to the optical fiber **12**, as shown in FIG. **1**. The chamber **34** holds the vanes **36** and the axle **32** at a specified pressure, optimal for thermal transpiration. The chamber **34** is evacuated to the appropriate vacuum level such that enough gas molecules are present to provide a transpiration force, but not enough for substantial drag forces to be incurred. Alternatively, a vacuum line is connected to the chamber **34** through the axle **32** during operation, such that the plurality of vanes **36** can adjust rotational speed **30** with minimal friction and distortion in rotation by varying the vacuum pressure of air molecules that create thermal transpiration. Alternatively, the rotational speed **30** of the light drive apparatus **22** can be controlled by varying the optical power **18** delivered to the vanes **36** or by a braking mechanism applied within the axle **32**. The vanes **36** may be shaped in a particular geometry to increase forces on the vanes **36** from thermally driven gas flow. Alternatively, vanes may consist of a single screw-type vane.

"Thermal transpiration" and "thermal creep" are terms employed to describe the physical principal involved in the transduction of optical energy **14** into mechanical energy **30**. When optical energy **14** impinges on the vanes **36**, the axle **32** starts rotating due to a radiometric force. The absorbent surface **42** of each vane becomes hotter than the reflective surface **40**, because of the different thermal absorption coefficients. The temperature or thermal gradient generates a force directed toward the colder reflective surface **42** as air molecules contained in the chamber **34** impinge on the vanes **36**. Air molecules at a low density exert different pressures on the hot absorbent surface **42** and on the cold reflective surface **40**.

In order to promote efficient rotation of axle **32**, the light drive apparatus **22** is positioned with an anterior bearing **52** and a posterior bearing **50** to minimize friction, as shown in FIG. **2**. The anterior **52** and posterior **50** bearings for the light drive apparatus **22** are designed to interface with the single mode (SM) optical fiber **12** and the Gradient Index lens **26** ("GRIN lens"). Because the tip of the SM optical fiber **12** must be positioned with respect to the GRIN lens **26**, the anterior bearing **52** is fabricated using LIGA to surround the SM optical fiber **12**, as shown in FIG. **3**. LIGA is a micromachining technology that employs high energy x-rays from a synchrotron to create high aspect ratio microstructures having micron to millimeter features. LIGA is an acronym for the German words for lithography, electroforming and molding. The GRIN lens **26** is operably bonded to the anterior bearing **52**. The material for the anterior bearing **52** is selected based on the coefficient of the kinetic friction between the optical fiber **12** and LIGA fabricated bearing **52**. The fiber **12** may be coated with a material that provides an effective contact surface with the LIGA fabricated bearing **52**.

The posterior bearing **50** must allow smooth, extremely low friction rotational motion of the axle **32** while preventing motion in the longitudinal or radial directions. In one embodiment, jewel or V-groove bearings made of hard and smooth surfaces such as sapphire will provide the most stability and less friction. Alternatively, magnetic and rolling bearings also can be used. The posterior bearing **50** can be fabricated using LIGA with material similar to those for the anterior bearing **52**. In one embodiment, the design of the posterior bearing **50** is a conical pointed tip bearing, as shown in FIG. **4**.

In operation, the GRIN lens **26** focuses energy **14** through a precisely controlled radial variation of the lens material's index of refraction from the optical axis to the edge of the lens **26**. This allows a GRIN lens **26** with flat or angle polished surfaces to collimate light **14** emitted from an optical fiber **12** or to focus an incident beam into an optical fiber **12**. The end faces of the GRIN lens **26** can be provided with an anti-reflection coating to avoid unwanted back reflection.

The light drive apparatus **22** generally comprises; (1) a GRIN lens **26** mounted onto an anterior bearing **52**, (2) a dichroic reflector element **24** or a prism, (3) an axle **32** carrying radially extending vanes **36**, and (4) a posterior bearing **50**. Each of these sub-components is joined together to form a linear array of the light drive apparatus **22**, as shown in FIGS. **2** & **3**.

In another embodiment the invention, a rotating tip catheter imaging probe **10** comprises a light drive apparatus **22** including a rotating element **100** and optical components **130**, as shown in FIG. **5**. The rotating element **110** includes a capillary tube **112** and a plurality of radial vanes **120** bonded to the lumen of the capillary tube **112**. The lumen of the capillary tube **112** is within an axle **118**, while a scattering material **114** fills the lumen **116** of the capillary tube **112**. The capillary tube **112** has an outer diameter of about 0.5 mm to about 1.0 mm in the outer diameter, while the lumen **116** has an inner diameter of about 50 microns. The capillary tube **112** is partially vacuum-sealed for optimal operation of thermal transpiration or thermal creep. The radial fins or vanes **120** have black and metallized surfaces bonded to proximal optical components **130** optimized for thermal transpiration or thermal creep, as discussed above.

The optical components **130** include a turbine input projection fiber **132**, prism reflecting fiber **134**, a gradient GRIN focusing fiber **136**, and a source optical fiber **138**, as shown in FIG. **5**. The GRIN focusing fiber **136** is rotatably coupled to the axle **118**, while the input projection fiber **132** is optically coupled to the lumen **116** of the axle **118**. In operation, energy **150** is transmitted from the source fiber **138** and is used to heat the plurality of vanes **120** provided along the axle **118** via the scattering material **114**, which deflects the optical energy to the plurality of vanes **120** within the capillary tube **112**. The scattering material **114** is selected such that the light incident from the end will scatter radially outward. The scattering coefficient of the material filling the inner lumen may be chosen so that scattering is of proper strength to allow light propagation along the axial length of the turbine. The stock length of the capillary tube **112** may be about 10-100 mm or longer. Alternatively, the glass of the capillary tube **112** can be doped with impurities to case scattering. The impurities can be metal or dielectric particles.

The radial fins or vanes **120** will run along the entire length of the axle **118** of the capillary tube **112**, as shown in FIG. **6**. The number of fins or vanes **120** will be at least one. In one embodiment, fin or vane **120** geometry is broader at the base and narrows toward the edge of the fin or vane. The metal selected to metallize the surface of the capillary tube **112** should be highly reflective at the drive wavelength. Alternatively, a single vane **120** may consist of a screw-type design to provide for efficient rotation by thermal transpiration.

Alternatively, the capillary tube **112** is bonded to encompass all of the optical components **130**, which include the turbine-input projection fiber **132**, a prism reflecting fiber **134**, and a GRIN focusing fiber **136**, as shown in FIG. **5**. The entire assembly is positioned and mounted in a partial vacuum-sealed capillary tube **112** and then positioned next to the terminus of the source optical fiber **138**. The optical energy is input axially to the rotating element **110** and can be collinear with the probe light energy, but only at a different wavelength. The rotating element **110** can be separated from the probe light by a dichroic film at the deflecting interface.

The invention also includes a method for directing optical energy for diagnostic or therapeutic purposes comprising, directing energy to a rotatably mounted vane member within a vacuum sealed chamber, coupling the vane member to a rotatably mounted reflecting element, rotating the vane member by operation of thermal transpiration as to rotate the reflecting element, and directing energy to the reflecting element. It should be appreciated that the light drive apparatus can be used in other optical imaging systems and spectroscopic measurements where optical energy is required to be delivered and collected.

The invention also comprises a method of manufacturing a light drive turbine comprises filling the inner lumen of a capillary tube, of about 0.5-1.0 mm in outer diameter and about 50 microns of inner diameter and about 10 mm in length, with a scattering material; mounting the capillary tube in a jig; laser machining radial vanes along the entire length of the capillary tube; metallizing the entire surface of the capillary tube; bonding a wire to the metal at a position on the capillary tube; removing the metal on one side of the vane; applying a potential to the bonded wire; depositing black positively charged electrophoretic ink on the vane surface; cutting the capillary tube into segments of about 1-2 mm; bonding these segments to proximal segments comprised of a turbine-input projection fiber, a prism reflecting fiber, and a GRIN focusing fiber; mounting the assembly in a partial vacuum sealed capillary tube; and providing proximal and distal bearings.

The wire bonded to the metal surface can be bonded anywhere on the entire surface of the capillary tube as long as it is convenient and accessible. The wire is used to vary the electrical potential in the step of depositing the black color.

Removing the metal on one side of the vane in the removal step can be achieved with laser machining or a spatially selective chemical etch. This results in the vane or fin which is metallized entirely, except for the regions on one side of each fin near the edge of the fin.

In the step of applying potential to the bonded wire, the metallized surface becomes electropositive or electronegative depending on the type of electrophoretic ink used. In one embodiment, a black electropositive ink is used in a deposition step, either chemical or vacuum deposition. When the metal film is charged electropositive, the black electropositive ink binds to the exposed glass surface.

EXAMPLE 1

Already, simulations of the imaging probe's turbine have been run using a Direct Simulation Monte Carlo (DSMC), with the initial conditions modified from a "Sone Thermal Creep" example to reflect the preferred embodiment of the turbine's vanes. This simulation is run at a very low temperature, and depicted thermal creep using the preferred embodiment of the vanes.

EXAMPLE 2

It is feasible to use the DSMC with modified initial conditions to run a simulation wherein the reference temperature is about 310 K (roughly the temperature within a human body), and starting both sides of the vane, absorbent and reflective, at the same 310 K temperature. This simulation demonstrates roughly the expected working conditions of the probe, and that there is enough force generated by thermal transpiration to rotate the probe assembly alone, without rotating the fiber running the length of the catheter.

It should be understood that while this invention has been described herein in terms of specific embodiments set forth in detail, such embodiments are presented by way of illustration of the general principles of the invention, and the invention is not necessarily limited thereto. Certain modifications and variations in any given material or process step will be readily apparent to those skilled in the art without departing from the true spirit and scope of the present invention, and all such modifications and variations should be considered within the scope of the claims that follow. The contents of the articles, patents, and patent applications, and all other documents mentioned or cited herein, are hereby incorporated by reference in their entirety to the same extent as if each individual publication was specifically and individually indicated to be incorporated by reference.

While the invention has been described in connection with various embodiments, it will be understood that the invention is capable of further modifications. This application is intended to cover any variations, uses or adaptations of the invention following, in general, the principles of the invention, and including such departures from the present disclosure as, within the known and customary practice within the art to which the invention pertains.

What is claimed is:

1. A method of making an optical imaging device, comprising the steps of:

providing a body having a central longitudinal lumen extending from a proximal end to a distal end of the body;

disposing an optical conduit within the central longitudinal lumen of the body and operably coupled with an optical imaging device;

disposing a rotating reflecting element at a distal end of the body in optical communication with the optical conduit;

positioning a gradient index lens proximal to the rotating reflecting element and in optical communication between the optical conduit and the rotating reflecting element;

mounting a plurality of vane members on a central rotary axle of the rotating reflecting element, wherein each of the plurality of vane members comprising an energy absorbing surface and an energy reflecting surface to provide for a thermal gradient when optical energy impinges on the plurality of vane members, and the rotating reflecting element further comprises a capillary tube having an inner lumen in optical communication with the optical conduit and the plurality of vane members are provided along the inner lumen, wherein the inner lumen includes a light scattering material for directing incident light toward the energy reflecting surface and the energy absorbing surface; and selecting a scattering coefficient for the light scattering material that scatters light incident radially outward.

2. A method of making an optical imaging device, comprising the steps of:

providing a body having a central longitudinal lumen extending from a proximal end to a distal end of the body;

disposing an optical conduit within the central longitudinal lumen of the body and operably coupled with an optical imaging device;

disposing a rotating reflecting element at a distal end of the body in optical communication with the optical conduit, the rotating reflecting in optical communication with the optical conduit;

positioning a gradient index lens proximal to the rotating reflecting element and in optical communication between the optical conduit and the rotating reflecting element; and

mounting a plurality of vane members on a central rotary axle disposed within an optically transparent tube, wherein each of the plurality of vane members having an energy absorbing surface and an energy reflecting surface to provide for a thermal gradient when optical energy impinges on the plurality of vane members, wherein the light drive apparatus is made by the steps of:

filling the optically transparent tube with a light scattering material having a scattering coefficient sufficient to propagate light along an entire longitudinal length of the optically transparent tube and doping the glass of the optically transparent tube with impurities to encase scattering within the optically transparent tube;

forming the plurality of radial vanes along the longitudinal length of the optically transparent tube;

metallizing the optically transparent tube and plurality of radial vanes with a light reflective metal;

removing the metallizing of the optically transparent tube on at least a portion of one side of each of the plurality of radial vanes;

applying an electrical charge to the metallization; and

depositing a charged energy absorbing material having a charge opposite the applied electrical charge to the metallization to preferentially bind the energy absorbing material to areas where metallization was removed.

3. The method of claim **1**, further comprising vacuum sealing the capillary tube.

4. The method of claim **3**, further comprising coupling an optical energy input axially through the rotating reflecting element and including a first optical energy, where the first optical energy is collinear with a second optical energy only at a different wavelength.

5. The method of claim **4**, further comprising separating the rotating reflecting element using a dichroic film at a deflecting interface.

6. The method of claim **5**, further comprising laser machining radial vanes along the entire length of the capillary tube.

7. The method of claim **6**, further comprising interfacing the gradient index lens with an anterior bearing and interfacing the optical conduit with a posterior bearing; and fabricating the anterior bearing with high energy x-rays from a synchrotron to create high aspect ratio microstructures.

8. The method of claim **7**, further comprising selecting the material for the anterior bearing based on the coefficient of kinetic friction between the optical conduit and the anterior bearing.

9. The method of claim **8**, wherein the posterior bearing is a V-groove bearing made of sapphire.

10. The method of claim **9**, further comprising providing an anti-reflection coating on the end faces of the gradient index lens to avoid back reflection.

11. The method of claim **2**, wherein the removing metallization is selected from laser machining and a spatially selective chemical etch.

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